TITLE: A SHORT INTRODUCTION TO THE STATUS AND MOTIVATION FOR REVERSED FIELD PINCH AND COMPACT TOROID RESEARCH

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A SHORT INTRODUCTION TO THE STATUS AND MOTIVATION FOR REVERSED FIELD PINCH AND COMPACT TOROID RESEARCH

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The achievement of controlled thermonuclear reactions will require ignition at a temperature well in excess of 4 keV, of a deuterium-tritium plasma whose confinement parameter $n\tau$ is larger than $10^{14}\,cm^{-3}s$. Experiments designed to achieve these conditions in the existing JET tokamak and the Compact Ignition Tokamak (CIT), planned in the U.S., are expected to occur in the early 1990s. In the interim, continued magnetic confinement research is required to develop the many improved features necessary for practical utilization of fusion in commercially viable power reactors. For example, important among these improvements for many confinement approaches is a practical steady-state current drive method. This would avoid the deleterious effects of cyclical fatigue brought on by pulsed reactor operation. Improved techniques for impurity control, refueling, and heating are also very desirable. In pure fusion systems there is also a need for more efficient utilization of the plasma confinement magnets than has been achieved so far in tokamak systems. The achievement of an adequate level of efficiency (i.e., high enough "beta"*), while maintaining good confinement, stability against disruptions, adequate steady-state current drive, the necessary heating

*Beta measures the amount of plasma pressure that can be confined by the pressure of the confining magnetic field.

and refueling capabilities, etc., is essential in the quest for practical fusion systems.

Potential commercial fusion power systems must be acceptable from a safety and environmental standpoint. They must also promise to be competitive with other sources of energy (i.e., fossil, fission, etc.) when considered from the standpoint of the cost of electricity (COE) and the unit direct cost (UDC) in ($/kWe). (See Figs. 1 and 2.) These costs are affected by a host of factors including recirculating power, plant availability, construction time, capital cost etc., and are, thus, influenced by technological complexity. Moreover, it is important in the realization of fusion power to keep the actual cost of fusion power development to an affordable level. This cost is directly related to the cost of each development step.

In an attempt to meet these requirements, the emphasis of fusion research in the United States has been moving toward smaller, lower-cost systems. There is increased interest in higher beta tokamaks and stellarators, and in compact alternate concepts such as the Reversed Field Pinch (RFP) and the Compact Toroids (CTs) which are, in part, the subject of this course and its workshops.

At this stage of magnetic fusion development it is not yet possible to choose the magnetic confinement concept which can ultimately satisfy the requirements of commercialization. When the remaining required nuclear technology and fusion material developments are considered, and the complicated interplay of all factors involved is taken into account, it becomes evident that the continued development of several different magnetic confinement approaches in addition to the tokamak provides a desirable breadth to the fusion program. In justifying RFP and CT research it is important to be aware of these basic programmatic motivations.

Introduction to RFP and CT Physics

The RFP and Compact Toroids (i.e., Spheromak and Field Reversed Configuration (FRC)) belong with the tokamak to the axisymmetric confinement class in which toroidal plasma current is an essential feature of confinement. In addition, the RFP and Spheromak, share with the tokamak, the basic utilization of a toroidal magnetic field. However, RFP and Spheromak confinement relies strongly on highly sheared self-magnetic fields (toroidal and poloidal) produced by the plasma, and, in contrast to the tokamak, requires only a moderate externally applied toroidal field (for the RFP) or none at all (for the Spheromak). The FRC, an elongated ("sheet") toroidal Z-pinch, operates without any internal or external toroidal field. (See Fig. 3 for typical field profiles for these configurations.) From these properties follows an important distinction with reactors consequences. The Compact Toroids require no toroidal field coils, while the RFP and the tokamak cannot operate without these. Consequently in the CT configuration there are no magnet coils or structured walls which have to link or extend through the torus, and this opens the possibility for these toroidal plasma configurations to be translated in space. (See Fig. 4 for a possible way to conceive an FRC reactor.) This translational degree of freedom is not available to the RFP or tokamak concepts. In these the plasma is constrained to a limited volume by toroidal field coils. The tokamak (see Fig. 3) operates at relatively small aspect ratio, R_T/r_p, with strong toroidal magnet coil fields, and a nominal toroidal plasma current limited by the Kruskal-Shafranov stability condition (i.e., the condition on the safety factor is approximately $q \gtrsim 1$). These high magnet fields and large required magnet currents and, to-date, relatively low predicted and observed plasma beta make it very difficult to conceive of a tokamak reactor that could operate with resistive magnet coils. The power consumption in resistive coils operating at high fields would be large, and superconducting coils are, therefore, required to avoid unacceptably large recirculating powers in the tokamak reactor. The thick shielding (~ 2 m), required to protect the superconducting coils from thermal flux and radiation damage, adds to the size of the components which surround the plasma chamber. The radial extent of these components, consisting of first wall, blanket, shielding, and magnets, must be about equal to the radius of the plasma chamber. Consequently an appreciable thickness of shielding leads to an increase in the size and mass of the entire fusion power core (FPC). (See Figs. 1 and 2 for a description of the FPC and other fusion plant components.)

Magnet requirements are greatly reduced when plasma self-magnetic fields are responsible for much of the confinement, as is the case for the RFP and the CT approaches. Projected reactors for such systems can use resistive magnets and require much less shielding. The size and mass of the fusion power core (FPC) of such reactor systems is expected to be 10-20 times smaller, and to be similar in size and mass to the comparable fission power core in a present-day pressurized water reactor (PWR). These more compact fusion systems therefore have the potential of meeting the goal of a mass power density (MPD) for the fusion power core in the range of 100-200 kWe/tonne. (See Fig. 3 for the percentage of total direct cost (TDC) required by the FPC and the reactor plant equipment (RPE) for a PWR and various conceptual fusion reactor designs.) The need and prospects for improved fusion reactors and the fusion reactor concepts introduced here are dealt with in much more detail elsewhere.[1,2]

The unique physics properties of the RFP and Spheromak are stabilization by high magnetic shear and maintenance of a minimum energy state plasma-magnetic field configuration[3] by a self-relaxation or dynamo process. This minimum energy state for the RFP is characterized by a toroidal magnetic field that maximizes in the plasma core, but reverses its direction near the edge of the plasma. For a given toroidal magnetic flux contained within a flux conserving boundary, this reversal takes place in a pinch for a sufficiently large value of the toroidal current. (The Spheromak is the special case for which the toroidal field vanishes at the plasma edge without reversing.) Taylor[3] discovered this state by minimizing the energy subject to the constraint of constant helicity, K, for the entire system. Helicity, defined by the volume integral

$$K = \int \mathbf{A}\cdot\mathbf{B}dv$$

where $\mathbf{A}$ and $\mathbf{B}$ are the vector potential and magnetic field, measures the linkage of different magnetic fields, e.g., toroidal and poloidal fields in the RFP and Spheromak. The concept of helicity, including its injection and decay, is developed and examined in several papers in these proceedings.

High magnetic shear and wall stabilization permit stable, low q, relatively high beta operation for the RFP and Spheromak configurations. Reports from most of the laboratories involved in these experiments are included in these proceedings. A central feature of these reports is the observed maintenance of a near minimum energy configuration by relaxation processes despite resistive diffusion and ohmic heating. Relaxation is now believed to occur when various three-dimensional MHD modes and fluctuations interact with each other. This activity originates at the rational surfaces where magnetic field lines, after (m,n) rotations about the minor and major toroidal axes, close on themselves. For the low q values in the RFP and Spheromak plasma cores ($q(r) \lesssim 1/(2R_T/r_p)$) there are many rational surfaces where such MHD activity and also magnetic islands can develop. A great deal of RFP research, some of which is reported in these proceedings, is now concerned with the relationship of this MHD activity and the magnetic island structure on relaxation and transport. Studies are also under way to evaluate a steady-state current drive technique which utilizes plasma nonlinearities associated with the minimum energy RFP configuration to rectify AC modulation imposed on the toroidal and poloidal field circuits.[4]

With no known limit to plasma current due to stability requirements, the RFP has the potential for ohmic heating to ignition. If this could be realized it would avoid the need for complex and costly auxiliary heating systems. The realization of this advantage and the advantage of compactness, described earlier, depends in large part on the ability to achieve adequate RFP confinement while maintaining an adequate beta at much higher toroidal currents. Two new devices under construction in the EC and USA, RFX and CPRF/ZTH, are designed to study these issues at much larger currents than have been achieved in existing devices. These new devices are also described in these proceedings. The locations and major features of the existing and large RFP experimental devices under construction in the European Community, Japan, and the United States are shown in Figs. 6 and 7.

The concept of helicity, its rate of decay and rate of injection, has been especially useful in describing the formation and sustainment of Spheromaks. (See Fig. 8 which illustrates schematically the "recipe" for forming the Spheromak.) In the case of the magnetized coaxial plasma gun (i.e., coaxial source) a steady state method for injecting helicity (i.e., plasma and linked poloidal and toroidal flux) has been demonstrated by maintaining voltage on the gun electrodes. This injection system involves direct contact of plasma with electrodes, and, therefore, impurity influx could be a major concern for any reactor embodiment based on this concept. However, the similarities between such an injection system and the magnetic divertor systems in use on tokamaks deserve to be studied. In any case, the use of DC voltage for steady state sustainment is technically so simple that much more research and development of this possibility is justified.

An inductive method for forming the Spheromak has also been placed into successful operation. For it a steady state current drive approach analogous to the one described for the RFP is potentially available. Spheromak research carried out with both the coaxial gun and inductive formation approaches are described in these proceedings.

As experience with the helicity concept has developed further, the decay of helicity in the edge of the Spheromak and the RFP has been investigated and recently proposed as a useful way to characterize the behavior of these systems.

Spheromak research is carried out at the Universities of Osaka and Tokyo in Japan, at Los Alamos, Princeton University, and University of Maryland in the U.S. and at the University of Manchester IST in Great Britain.

Field Reversed Configuration (FRC) research deals with a prolate shaped toroidal plasma which is confined solely by poloidal closed and open field lines. In contrast, Spheromaks, to be MHD stable must be oblate in shape. (See Fig. 9.) It is possible to reach the highest betas (i.e., $\beta \approx 1$) with the prolate FRC configuration, because it operates without toroidal magnetic field. All of the plasma pressure can be supported by the poloidal field surrounding the plasma. Existing FRC experiments, described in these proceedings, routinely produce plasmas that have diameters 10-20 cm, length $\approx$ 100 cm, $1 \times 10^{21} m^{-3} \leq n_e \leq 5 \times 10^{21} m^{-3}$, average $\beta \simeq 1$, $0.1 \leq T_i \leq 0.6$ keV, $0.1 \leq T_e \leq 0.2$ keV, and $\tau_E \leq 100$ μs. Such plasmas can be formed using the field-reversed theta pinch technique and can be translated into and along a nearly uniform magnetic guide field without loss of plasma energy. During their subsequent motion over distances that are large compared to their length the FRCs maintain their integrity with no loss in their confinement.

The motivation for FRC research is the possibility of producing a $\beta \sim 1$ "cylinder of plasma" that can be translated along a uniform magnetic field. As indicated in Fig. 4, formation, heating to ignition, burn, and fuel exhaust could be carried out in separated regions of space. In many ways this would be the ideal magnetic fusion reactor. It might be capable of very large fusion power density and very large neutron wall loads, and might utilize these extreme burn conditions with technically simple blankets, possibly consisting of movable rods or even circulating liquid metal "curtains." Moreover, it might be possible to utilize this system with the higher temperatures required to burn advanced fuels, since the strong diamagnetism associated with $\beta \sim 1$ would greatly reduce synchrotron radiation.

The assessment of the FRC as a practical configuration for fusion power applications requires a sustained international research effort that develops improved formation, investigates stability and transport properties, and demonstrates effective heating techniques. The unexpected MHD stability observed for the FRC plasma against the $m = 0$ "sausage" and $m = 1$ "kink" (also known as the internal "tilt") is now thought to be explainable in terms of its favorable pressure profile (i.e., it satisfies the Kadomtsev condition for m = 0 stability) and in terms of stabilization by ion kinetic effects for the internal tilt mode. Control of the n = 2 rotational mode, first demonstrated in Japan with the help of externally applied multipole fields has been verified by other FRC experimenters. The internal tilt mode, however, remains a serious threat to the utilization of the FRC for fusion purposes. As experiments advance towards more reactor-relevant plasma conditions, the average number of ion gyro radii contained in the cross-section of the FRC plasma, $\bar{s}$, will increase and stabilization due to ion kinetic effects is expected to become less important. Recent FRC instability computations, described in these proceedings, which include ion kinetic effects have been carried out as a function of $\bar{s}$. These indicate that the growth rate for the internal tilt mode is expected to increase with increasing $\bar{s}$. This is a very important prediction, because the internal tilt instability is expected to result in field line tearing that reconnects closed poloidal field lines to open poloidal field lines and thus spoils confinement. (See Fig. 10.) If the predictions are borne out by experimental observation it will become essential to find a method of stabilization for the tilt mode. New experimental FRC devices now under construction in the USA are designed to investigate the important issues of stability, transport and heating.

REFERENCES

1. R. A. Krakowski, R. L. Miller, and R. L. Hagenson, J. Fusion Energy 5, 213 (1986).

2. R. K. Linford, New Directions in Fusion Machines: Report on the MFAC Panel X High Power Density Options.

3. J. B. Taylor, Phys. Rev. Lett. 33, 1139 (1974).

4. K. F. Schoenberg et al., J. Appl. Phys. 56, 2519 (1984).

FIGURE CAPTIONS

Fig. 1. Essential elements of a fusion power plant showing main economic, safety and environment (S&E), and product input/output aspects.

Fig. 2. Essential elements determining the cost of a fusion power plant, the cost of electricity, as well as the major components of the Reactor Plant Equipment (RPE, Account 22.) and the Balance of Plant (BOP).

Fig. 3. Family of toroidal fusion concepts showing toroidal, B_ϕ, and poloidal fields, B_θ, along with the relative aspect ratios, R_T/r_p.

Fig. 4. Schematic of possible FRC reactor approach.

Fig. 5. Percentage of total direct cost required by the RPE and FPC for a range of recent conceptual fusion reactor designs.

CSR	= Compact Spheromak reactor
CPRF	= Compact RFP reactor
ATR/ST	= Advanced Tokamak reactor based on Spherical Torus
MARS	= Mirror Advanced reactor
STARFIRE	= Tokamak reactor (recent)
UWMAK	= Tokamak reactor (earlier)

Fig. 6. Location and features of RFP experimental devices.

Fig. 7. Location and features of RFP experimental devices.

Fig. 8. Flux behavior in Spheromak formation.

Fig. 9. Schematic of oblate Spheromak and prolate FRC.

Fig. 10. Evolution of the internal tilt mode in the absence of ion kinetic stabilization. Presented by D. C. Barnes, R. Bishop, D. D. Schnack, and R. Milroy at the Sherwood Theory Conference, April 6-8, 1987, San Diego, CA.

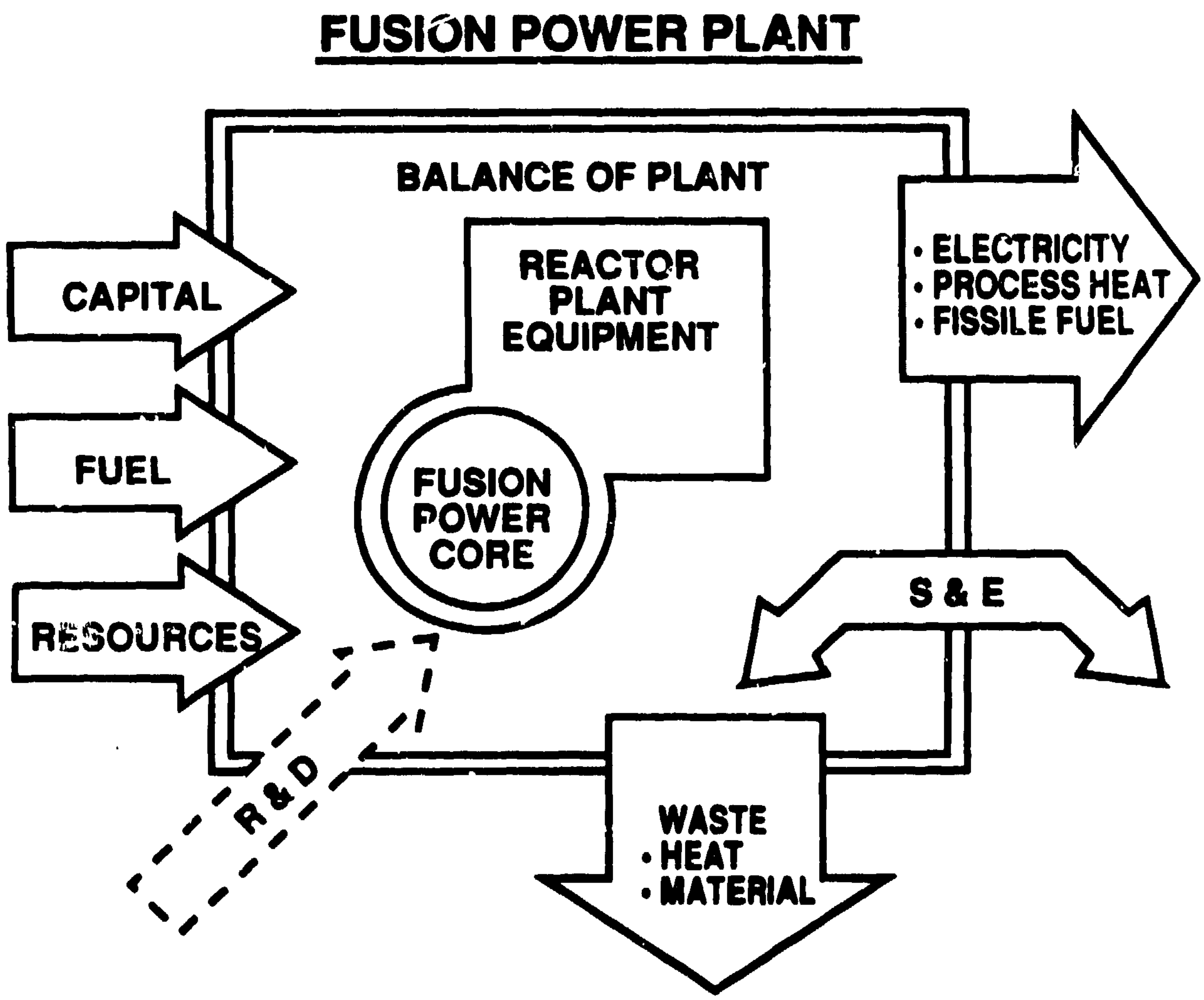
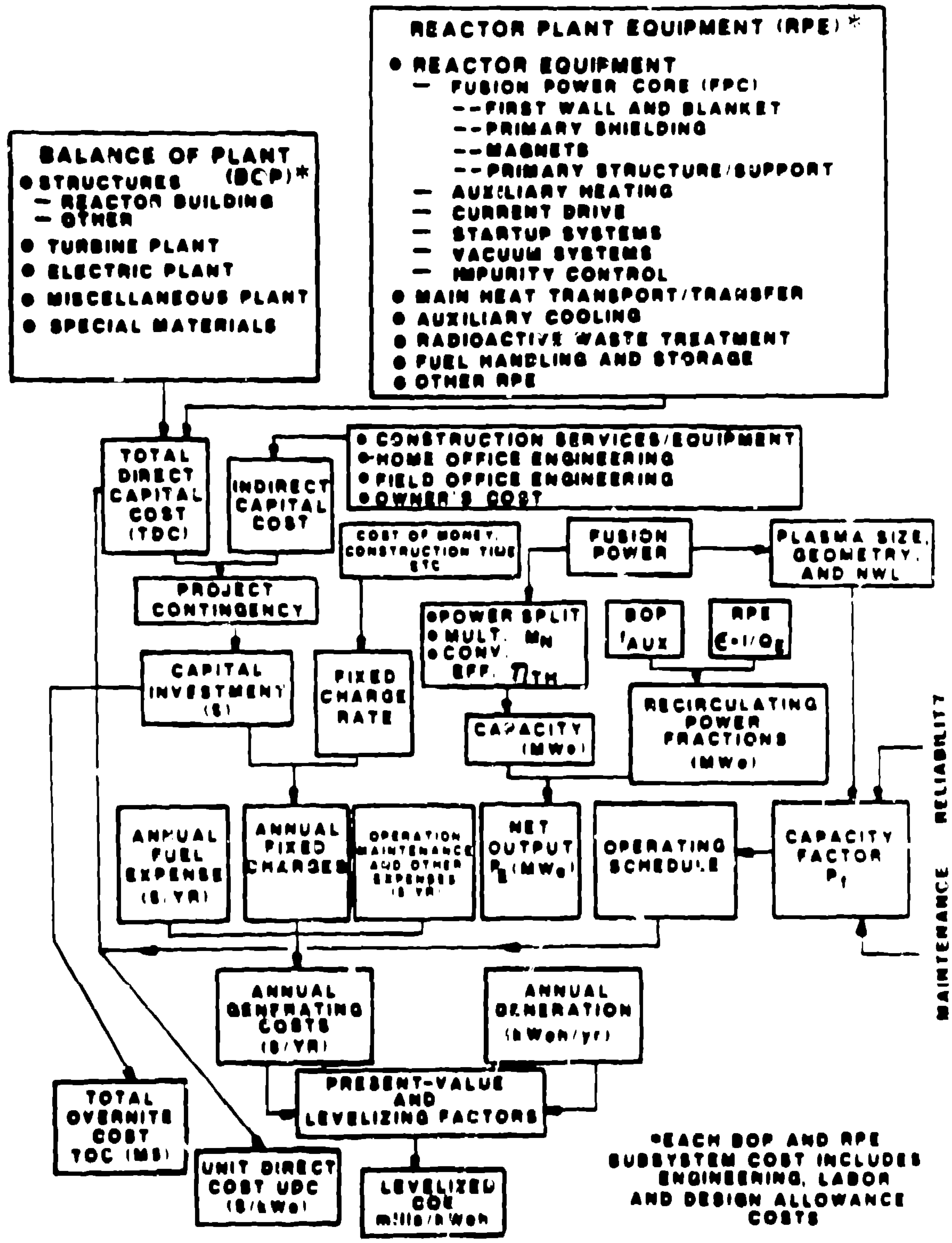
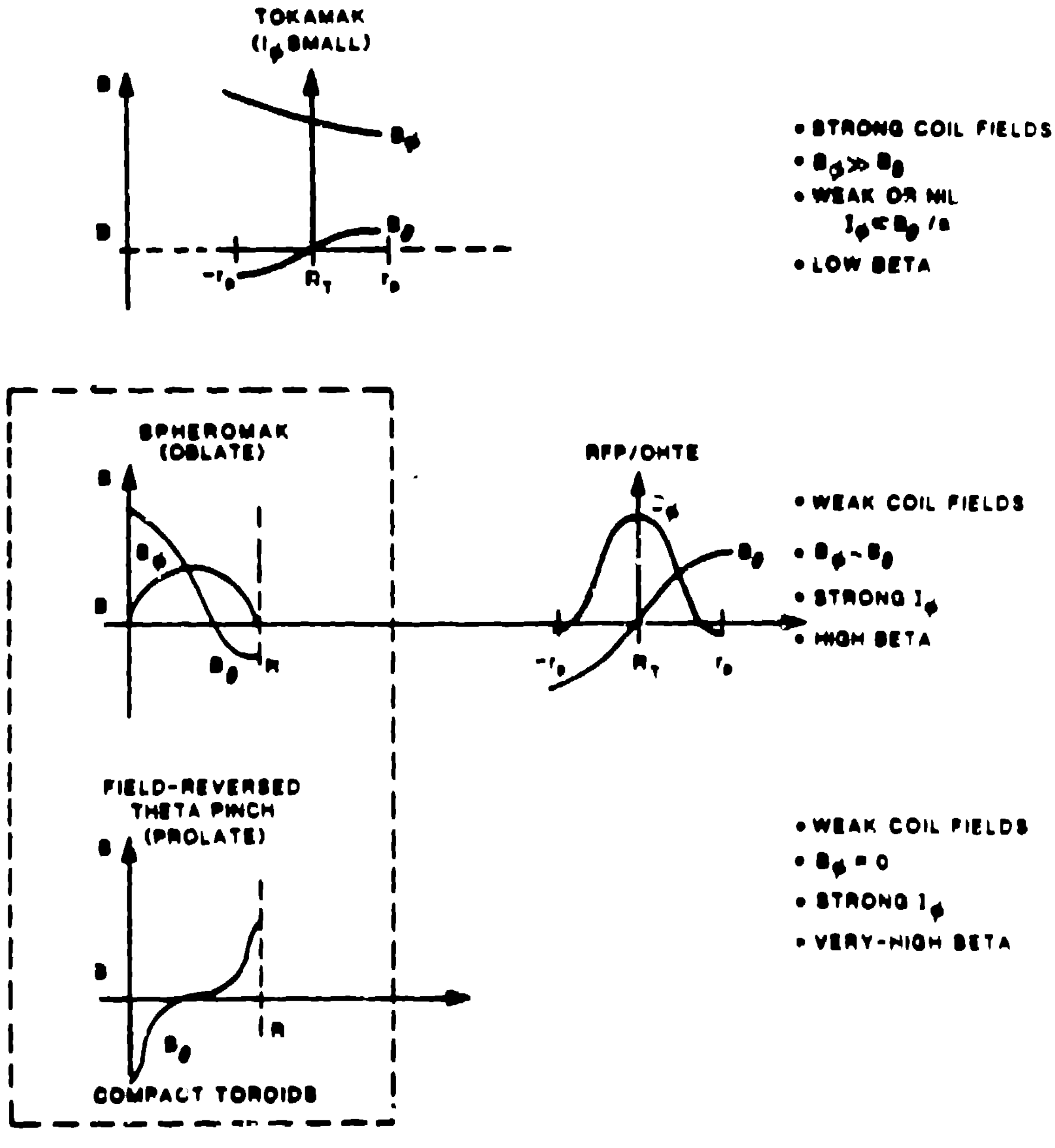

FUSION POWER PLANT
BALANCE OF PLANT
REACTOR PLANT EQUIPMENT
FUSION POWER CORE
CAPITAL
FUEL
RESOURCES
R&D
• ELECTRICITY
• PROCESS HEAT
• FISSILE FUEL
S & E
WASTE
• HEAT
• MATERIAL

FIG. 1.



REACTOR PLANT EQUIPMENT (RPE)*
● REACTOR EQUIPMENT
— FUSION POWER CORE (FPC)
--FIRST WALL AND BLANKET
--PRIMARY SHIELDING
--MAGNETS
--PRIMARY STRUCTURE/SUPPORT
— AUXILIARY HEATING
— CURRENT DRIVE
— STARTUP SYSTEMS
— VACUUM SYSTEMS
— IMPURITY CONTROL
● MAIN HEAT TRANSPORT/TRANSFER
● AUXILIARY COOLING
● RADIOACTIVE WASTE TREATMENT
● FUEL HANDLING AND STORAGE
● OTHER RPE
BALANCE OF PLANT (BOP)*
● STRUCTURES
— REACTOR BUILDING
— OTHER
● TURBINE PLANT
● ELECTRIC PLANT
● MISCELLANEOUS PLANT
● SPECIAL MATERIALS
TOTAL DIRECT CAPITAL COST (TDC)
INDIRECT CAPITAL COST
● CONSTRUCTION SERVICES/EQUIPMENT
● HOME OFFICE ENGINEERING
● FIELD OFFICE ENGINEERING
● OWNER'S COST
PROJECT CONTINGENCY
COST OF MONEY, CONSTRUCTION TIME ETC
FUSION POWER
PLASMA SIZE, GEOMETRY, AND NWL
●POWER SPLIT
●MULT. M_N
●CONV. EFF. η_{TH}
BOP f_{AUX}
RPE $\epsilon = 1/Q_E$
CAPITAL INVESTMENT ($)
FIXED CHARGE RATE
CAPACITY (MWe)
RECIRCULATING POWER FRACTIONS (MWe)
RELIABILITY
MAINTENANCE
ANNUAL FUEL EXPENSE ($/YR)
ANNUAL FIXED CHARGES
OPERATION MAINTENANCE AND OTHER EXPENSES ($/YR)
NET OUTPUT P_E (MWe)
OPERATING SCHEDULE
CAPACITY FACTOR P_f
ANNUAL GENERATING COSTS ($/YR)
ANNUAL GENERATION (kWeh/yr)
PRESENT-VALUE AND LEVELIZING FACTORS
TOTAL OVERNITE COST TOC (M$)
UNIT DIRECT COST UDC ($/kWe)
LEVELIZED COE mills/kWeh
*EACH BOP AND RPE SUBSYSTEM COST INCLUDES ENGINEERING, LABOR AND DESIGN ALLOWANCE COSTS

FIG. 2.



TOKAMAK
(I_ϕ SMALL)
B
B_ϕ
B_θ
$-r_p$
R_T
r_p
• STRONG COIL FIELDS
• $B_\phi \gg B_\theta$
• WEAK OR NIL
$I_\phi < B_\theta / a$
• LOW BETA
SPHEROMAK
(OBLATE)
B_ϕ
B_θ
R
RFP/OHTE
B_ϕ
B_θ
$-r_p$
R_T
r_p
• WEAK COIL FIELDS
• $B_\phi \sim B_\theta$
• STRONG I_ϕ
• HIGH BETA
FIELD-REVERSED
THETA PINCH
(PROLATE)
B_θ
R
COMPACT TOROIDS
• WEAK COIL FIELDS
• $B_\phi = 0$
• STRONG I_ϕ
• VERY-HIGH BETA

FIG. 3.

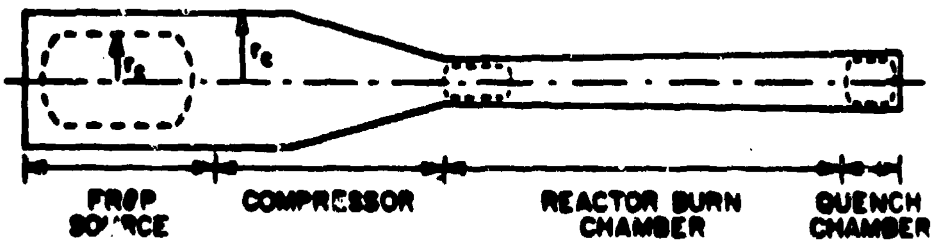


FIG. 4.

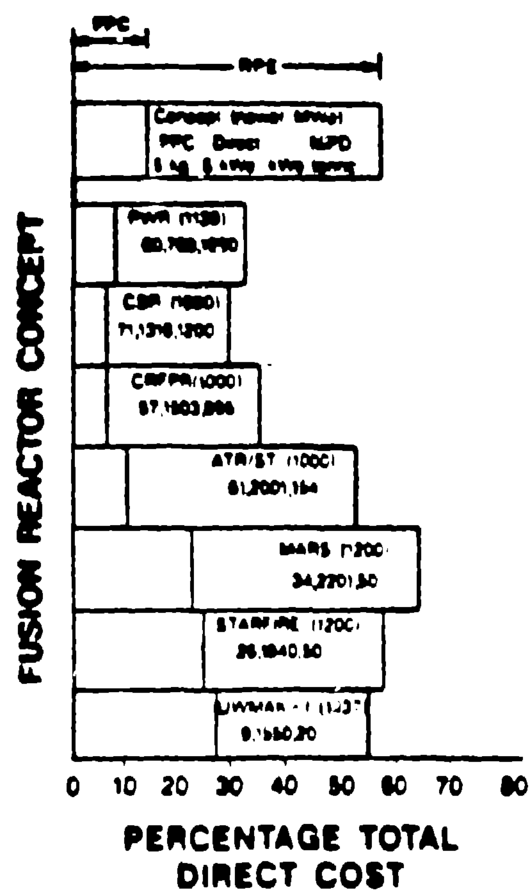

FUSION REACTOR CONCEPT
ATR/ST (1000)
MARS (1200)
0 10 20 30 40 50 60 70 80
PERCENTAGE TOTAL
DIRECT COST

FIG. 5.

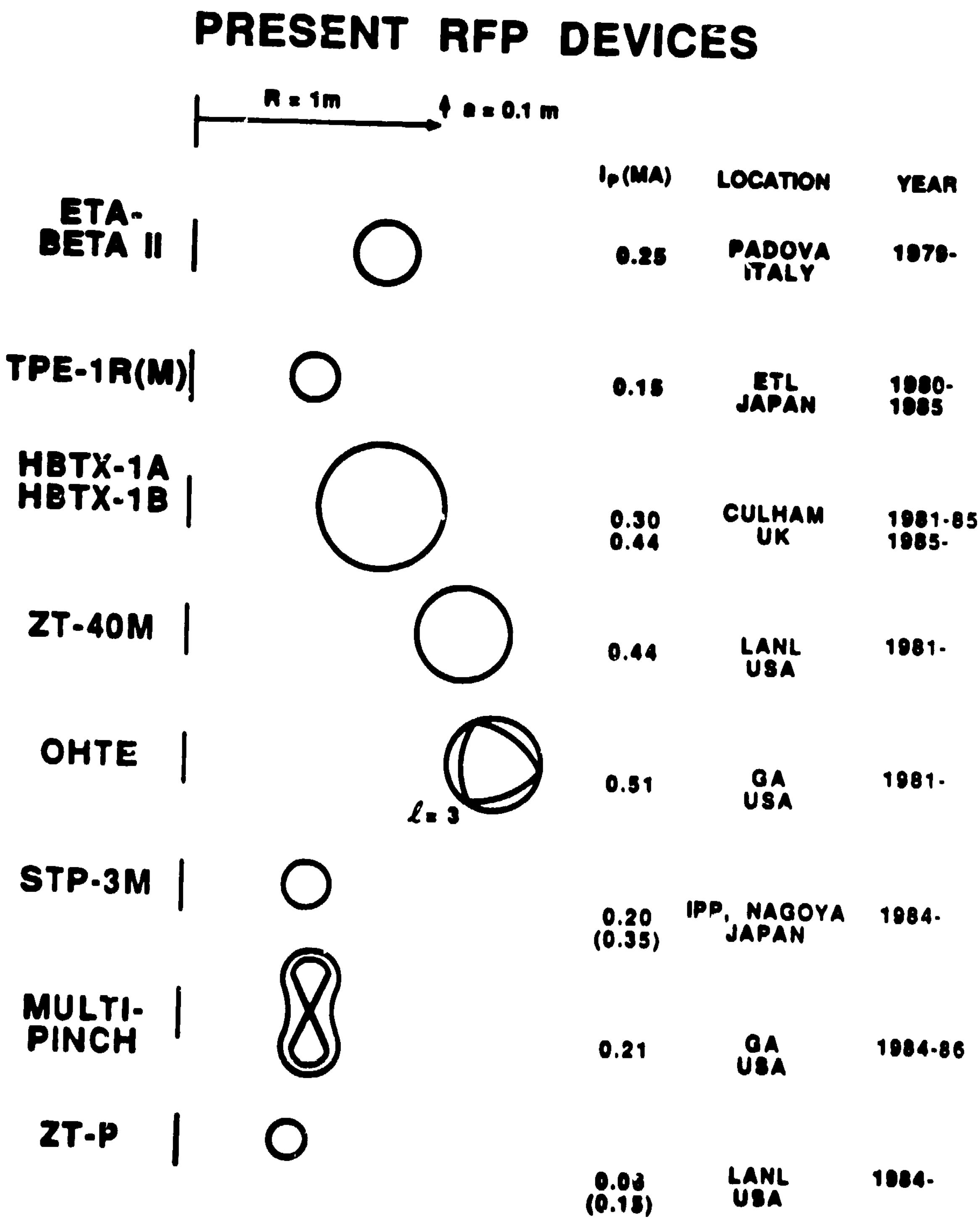
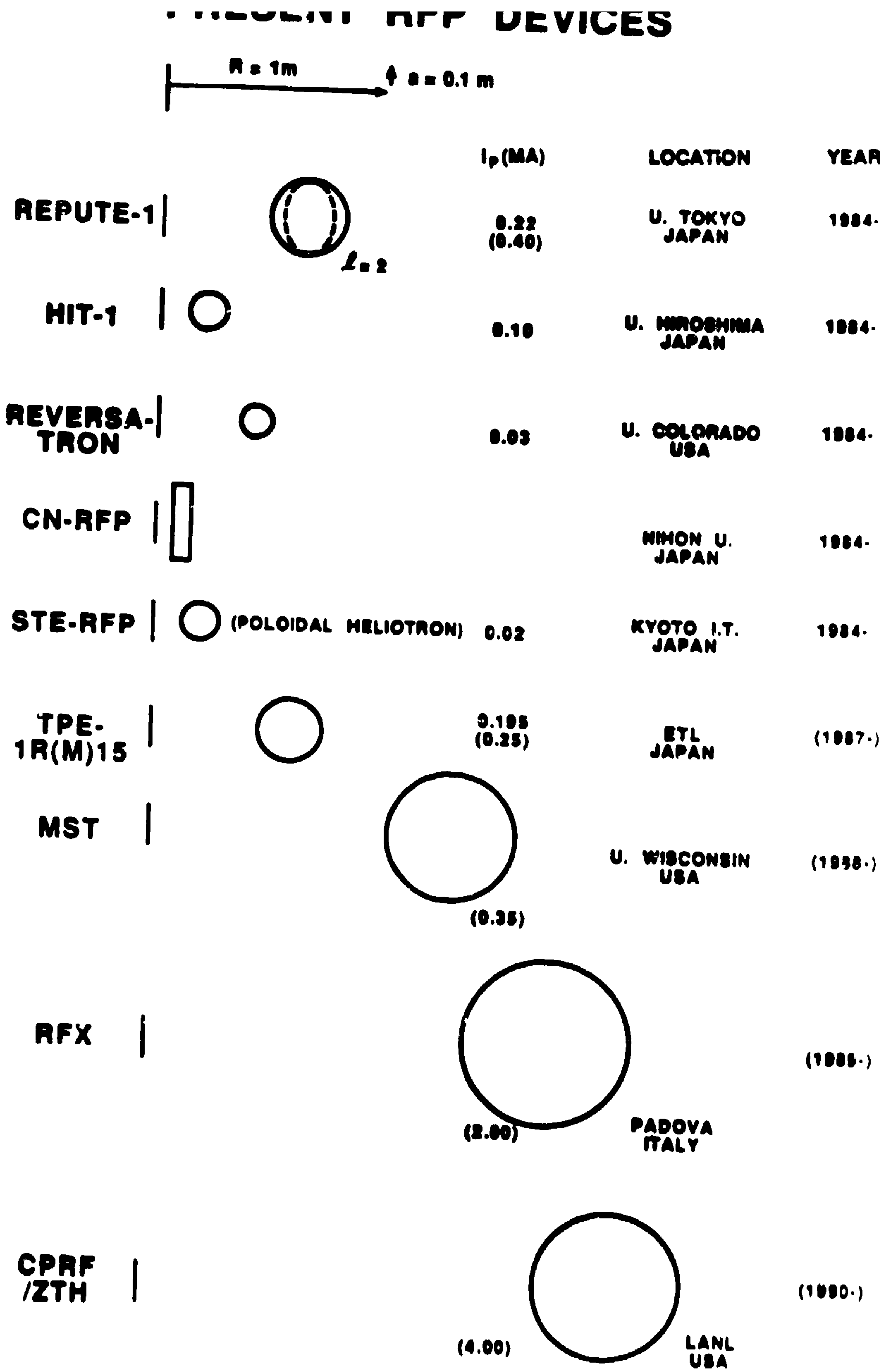

PRESENT RFP DEVICES
R = 1m
a = 0.1 m
Ip(MA)
LOCATION
YEAR
ETA-BETA II
0.25
PADOVA ITALY
1979-
TPE-1R(M)
0.15
ETL JAPAN
1980-1985
HBTX-1A
HBTX-1B
0.30
0.44
CULHAM UK
1981-85
1985-
ZT-40M
0.44
LANL USA
1981-
OHTE
ℓ = 3
0.51
GA USA
1981-
STP-3M
0.20
(0.35)
IPP, NAGOYA JAPAN
1984-
MULTI-PINCH
0.21
GA USA
1984-86
ZT-P
0.03
(0.15)
LANL USA
1984-

FIG. 6.



DEVICES
R = 1m
a = 0.1 m
I_p(MA)
LOCATION
YEAR
REPUTE-1
$\ell = 2$
0.22
(0.40)
U. TOKYO
JAPAN
1984-
HIT-1
0.10
U. HIROSHIMA
JAPAN
1984-
REVERSA-
TRON
0.03
U. COLORADO
USA
1984-
CN-RFP
NIHON U.
JAPAN
1984-
STE-RFP
(POLOIDAL HELIOTRON)
0.02
KYOTO I.T.
JAPAN
1984-
TPE-
1R(M)15
0.195
(0.25)
ETL
JAPAN
(1987-)
MST
U. WISCONSIN
USA
(1988-)
(0.35)
RFX
(2.00)
PADOVA
ITALY
CPRF
/ZTH
(1990-)
(4.00)
LANL
USA

FIG. 7.

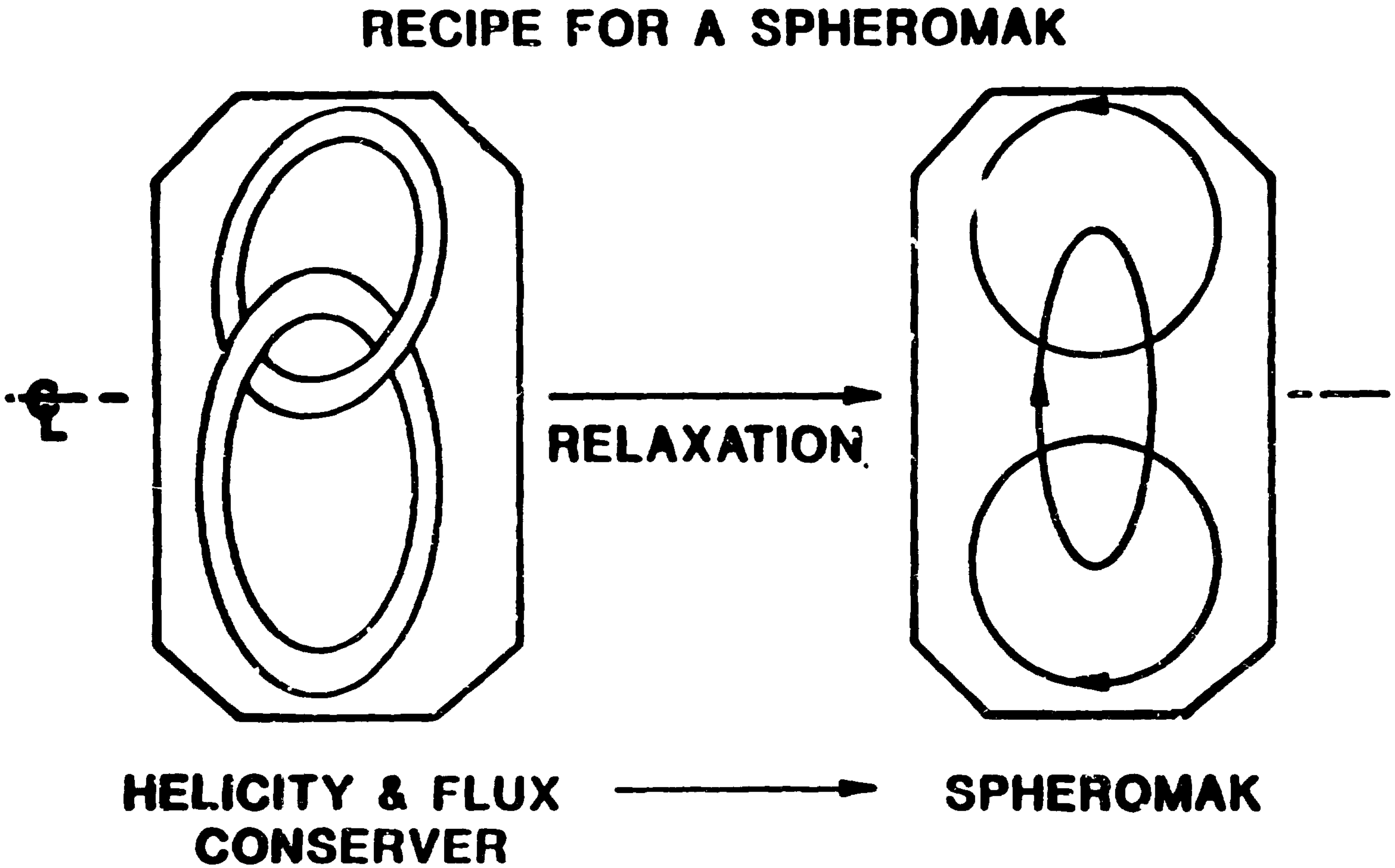

RECIPE FOR A SPHEROMAK
RELAXATION
HELICITY & FLUX
CONSERVER
SPHEROMAK

FIG. 8.

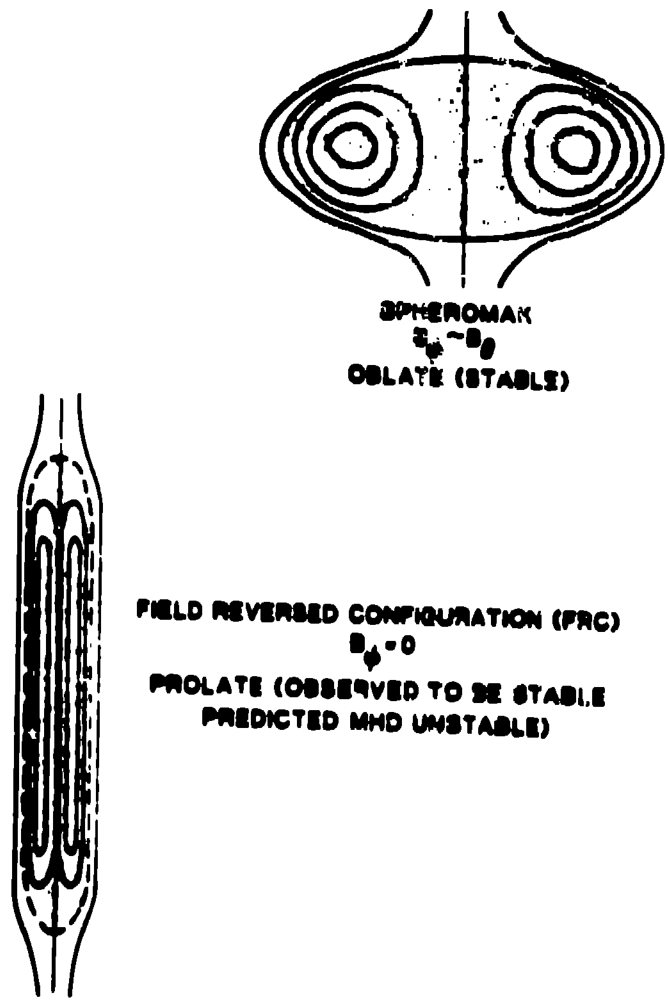

SPHEROMAK
$B_\phi \sim B_\theta$
OBLATE (STABLE)
FIELD REVERSED CONFIGURATION (FRC)
$B_\phi = 0$
PROLATE (OBSERVED TO BE STABLE
PREDICTED MHD UNSTABLE)

FIG. 9.

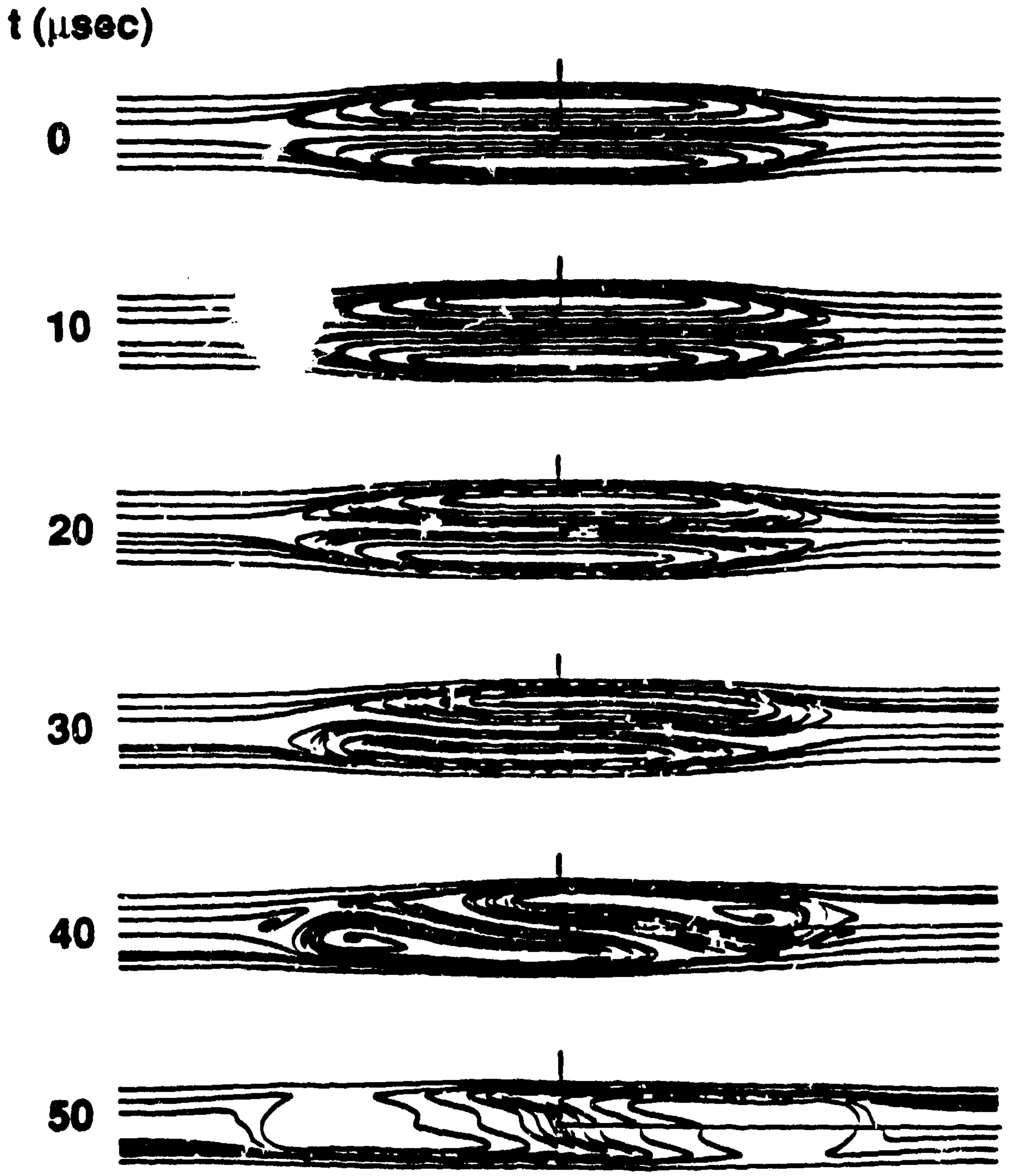


FIG. 10.